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ABSTRACT

High resolution vacuum ultraviolet spectra of carbon, oxygen, and nitrogen impurity ions in a neutral beam heated mirror confinement plasma have been observed. The line intensity ratios for Li-like C IV and N V are consistent with excitation by electron impact, however, the O VI line intensities imply an anomalously high $(1s)^2 3d$ population. The role of charge exchange of these ions with the injected neutral beams is investigated. Our analysis shows that the anomalous ratios can be explained by charge exchange processes, and thus provides important diagnosis for helium-like ionization stages such as O VII which are difficult to observe directly.

INTRODUCTION

High-resolution spectroscopy of impurity ion radiation is a powerful plasma diagnostic tool, both for monitoring the impurity concentration and for measuring plasma parameters. The measured spectra do however depend on a detailed understanding of the atomic processes responsible for excitation and emission of the ionized impurity species in the plasma. As our knowledge of these cross-sections and rates grows, so does our ability to interpret the spectra and in turn to diagnose the system.

In this paper we report results for the lithium-like vacuum-ultraviolet spectra of carbon, oxygen, and nitrogen impurities in the LLNL TMX-U magnetic mirror plasma facility (Grubb 1984). The C^{+3} and N^{+4} line intensities we observe are consistent with excitation by electron impact, but the O^{+5} intensities are not. We show that this anomaly can be explained by the charge transfer reaction of helium-like O^{+6} with the D^0 injected in neutral beam heating,

$$O^{6+} + D^0 \rightarrow (O^{5+})^* + D^+ \quad .$$

We use recently measured experimental values of the cross-sections for the transfer into specific excited substates (Ciric et al) to interpret our experimental results.

Previous studies (Isler et al 1978) at the ISX-A Tokamak have also shown anomalous line intensities in O^{5+} and O^{6+}, and have explained the intensity variations by charge exchange. Our data show similar effects, but we can use the recently measured cross-sections to interpret our results without relying on theoretical calculation.

Experimental Procedure

In the TMX-U device, a plasma is confined radially by magnetic fields and axially by magnetic field gradients and by electrostatic fields which are created by preferentially heating either ions or electrons in the end plugs. The details of the plug potential profiles as formed by the interaction of ECR heated electrons and sloshing ion beams are well documented elsewhere (Coensgen et al 1980). Central cell densities are between 10^{11} and 10^{13} cm^{-3} with central cell electron temperatures between 10 and 200 eV. Central cell ions are heated by both neutral beams and ICRH so that approximately 30% have energies of several kilovolts while the remainder have energies of the order of the electron temperature. The energy of the dominant component of the neutral beams is 8 keV and the total neutral beam flux is 0.1 A/cm^2. Plasma durations are typically several tens of milliseconds.

We view the TMX-U central cell plasma with a 2 meter grazing incidence vacuum-ultraviolet spectrometer. The detector is a microchannel plate image intensifier read by a 1024 channel linear photodiode array with a 4 ms readout time. Thus we acquire $\sim$20 4 ms spectral frames during a plasma shot and can follow the time development of the impurity emissions with a 4 ms time resolution. Spectral resolution, $\lambda/\Delta\lambda$, is about 1,000. Gratings may be interchanged so that any line in the range of 10-2000 angstroms may be observed, but the spectral range in one shot is much more limited. For instance with a 2400 l/mm grating we may obtain spectra over a range of 25 angstroms. The horizontal field of view is f/40; the vertical field of view depends upon the detector position. The spectrometer line of sight is a chord through the central cell plasma which intersects several central cell neutral beam trajectories. A diagram of the apparatus is shown in Fig. 1.

RESULTS

Figure 2 shows a partial level diagram for the lithium-like sequence, with values for the transition wavelengths and branching ratios given for O^{+5}. We have measured the n = 3 → n = 2 lines for this sequence, in particular the 3s → 2p and 3d → 2p lines, under different plasma conditions.

Defining the intensity ratio of these two lines as Γ = I(3d→2p)/I(3s→2p), we can evaluate Γ for the Li-like sequence, assuming only excitation by electron impact. For the electron temperatures we observe, we expect $\Gamma \approx 2$ (±20%) for the three impurity elements we observe.

Figure 3 shows these two O^{+5} lines observed during the steady state emissions of Shot 15 on 20 January, 1983. One notices that the intensity ratio, Γ, of the two lines is about 4.0 rather than the value of 2.0 predicted by electron impact excitation. Γ remains constant at 4.0 throughout the shot. Also the intensity ratio of the O^{+5} 173 A line to the nearby O^{+4} 172 A line indicates that there is much more O^{+5} that O^{+4} in the plasma on this shot. Other temperature diagnostics report a T_e of ≈100 eV on this shot. We measured values for Γ ranging from 3 to 4 on this date.

In Fig. 4 we present the same spectrum from Shot 29 of 8 February, 1984. Notice that this shot is colder as the O^{+5} and O^{+4} lines have roughly equal intensity. In this shot the ratio of the O^{+5} intensities, Γ, is 2, consistent with electron impact excitation predictions. The electron temperature on this shot was 50 eV.

Data for the intensities of Li-like C and N are summarized together with the O results in Table I. These lines seem to be in agreement with intensities as predicted (Sampson and Golden 1978; Heroux et al 1972) by electron impact excitation. We have, however, observed anomalous ratios in N V during an experiment in which nitrogen was beam injected into the plasma, but we will not discuss those results here.

Summarizing, our observations of C IV and N V 3-2 transitions are consistent with electron impact excitation. For the O VI 3-2 transitions, the cold plasma line intensity ratios are also consistent with electron impact excitation predictions, but the hotter shots produce line intensities which differ substantially from these predictions. It should be noted that electron impact excitation predictions agree well with simple radiative oscillator strengths for the same lines (Sampson and Golden 1978; Heroux et al 1972). The measured differences between our experiment and electron impact theory are well outside observational uncertainties.

The process of charge exchange excitation offers an explanation of the observed phenomena. In the hotter plasmas we expect a large fraction of the impurities to be in the helium-like states, which because of their large excitation energies, will not radiate. The helium-like O^{+6} is therefore unobservable by spectroscopy in the temperature range accessable at TMX unless it charge exchanges with a neutral deuterium atom. The charge exchange reaction leaves the product O^{+5} in a distribution of excited states, a distribution which is in general quite different from the excited state population derived from electron impact. Thus our picture of the phenomenon is that of an impurity ionization balance dominated by the helium-like sequence, which in turn yields a lithium-like spectrum, driven by charge exchange, as a unique signature.

ANALYSIS

At the electron densities characteristic of TMX-U, radiative lifetimes of excited atomic states are of the order of nanoseconds, much faster than the millisecond time scales for collisional processes such as excitation or scattering. The ion bounce times to traverse the length of the central cell are on the order of microseconds. One can then neglect collisional depopulation of most excited states, except for low-lying metastable states, and average excitation processes over the central cell volume.

Our analysis assumes that the experimental plasma rates are all slower than the individual atomic rates. Thus steady state rate equations are appropriate. In our rate equations we include radiative decay, electron impact excitation, and terms due to collisions with the energetic neutral beams. For our plasma conditions the charge exchange completely dominates electronic recombination in determining the ionization balance. For the C IV and N V excited state populations, we show that charge exchange collisions with the neutral beams do not alter the ratios from the predictions based on electron impact excitation. In the case of O VI the charge exchange recombination of O VII with energetic beam neutrals plays a larger role. Our rate equations provide expressions for the rates of population of the n = 3 levels of O VI.

For the steady state population of the 3d level of the lithium-like ionic sequence we have

$$\mathring{n}_{3d} = 0 = n_e n_{\ell i} \langle \sigma_{3d} v_e \rangle + n_b n_{he} \sigma_{cx3d*} v_b - n_{3d} A_{3d} \; . \qquad (1)$$

Here n_e, n_{li}, n_{he}, n_{3d}, and n_b, are the densities of electrons, ground state lithium-like and helium-like impurities, lithium-like impurity in the 3d level, and beam neutrals; v_e and v_b are electron and beam velocities, σ_{3d} is the electron impact cross-section, σ_{cx3d*} is the cross section for the charge exchange recombination processes that populate the 3d level including cascade after charge exchange, and A_{3d} is the radiative decay rate for the 3d level. The intensity of the 3d-2p line is then

$$I_{3d} \equiv n_{3d}A_{3d} = n_e n_{\ell i}\langle\sigma_{3d}v_e\rangle + n_b n_{he}\sigma_{cx3d*}v_b \quad . \tag{2}$$

A similar set of equations holds for the 3s population and 3s-2p intensity.

We calculate the 3d - 3s intensity ratio, Γ, to be,

$$\Gamma = \frac{n_e n_{\ell i}\langle\sigma_{3d}v_e\rangle + n_b n_{he}\sigma_{cx3d*}v_b}{n_e n_{\ell i}\langle\sigma_{3s}v_e\rangle + n_b n_{he}\sigma_{cx3s*}v_b} \quad . \tag{3}$$

For the O VII case, virtually all of the charge exchange is into the n = 4 excited levels (Ciric et al; Shipsey et al 1981). As shown in Fig. 2 all of the 4f state and essentially none of the 4p state will decay to 3d, while 21% of the 4p state will decay (Martin et al 1976) to 3s. The 3d to 3s ratio becomes

$$\Gamma = \frac{\langle\sigma_{3d}v_e\rangle + \frac{n_b}{n_e}\frac{n_{he}}{n_{\ell i}} v_b \left(\sigma_{cx4f} + \sigma_{cx3d}\right)}{\langle\sigma_{3s}v_e\rangle + \frac{n_b}{n_e}\frac{n_{he}}{n_{\ell i}} v_b \left(.21\sigma_{cx4p} + \sigma_{cx3s}\right)} \quad . \tag{4}$$

For the conditions of 1-20-83 shot 15 we have an electron temperature of about 100 ev, and electron impact excitation rates (Sampson and Golden 1978; Heroux et al 1972) as

$$\langle\sigma_{3d}\, v_e\rangle = 8. \times 10^{-10}\ \mathrm{cm^3/s} \quad ,$$

$$\langle\sigma_{3s}\, v_e\rangle = 4. \times 10^{-10}\ \mathrm{cm^3/s} \quad .$$

On this shot $n_b/n_e = 10^{-3}$ and $v_b = 10^8$ cm/sec.

We take the oxygen charge exchange recombination partial cross-sections from recently measured experimental results (Ciric et al.) at 3.75 keV/amu:

$$\sigma_{cx4f} = 8.7\ A^2 \qquad (\pm 25\%)$$
$$\sigma_{cx4p} = 3.7\ A^2 \qquad "$$
$$\sigma_{cx3d} = 2.7\ A^2 \qquad "$$
$$\sigma_{cx3s} = 0.4\ A^2 \qquad " \quad .$$

Using these values the expression for Γ(O VI) becomes, within 35% error,

$$\Gamma = \frac{2.2 + 0.3\,\frac{n_{he}}{n_{\ell i}}}{1 + 0.03\,\frac{n_{he}}{n_{\ell i}}} \quad . \tag{5}$$

The measured range of Γ between 3.0 and 4.0 implies values of n_{he}/n_{li} ranging from 4 to 10. For oxygen the partial charge exchange cross sections are mildly sensitive to the beam energy (Ciric et al). At collision energies above 3.75 kev/amu the 4f and 3d cross sections increase while the 4p and 3s cross sections decrease, making Γ more sharply dependent on n_{he}/n_{li}. At collision energies below 3.5 kev/amu Γ is less sensitive.

If the data of de Heer et al. are used to analyze our N V data, the intensity ratio of the 3d-2p to the 3s-2p line is predicted to be about 2 by both electron impact and charge exchange recombination. The model as applied to carbon would actually cause the 3d/3s population ratio to dip below two as charge exchange becomes more dominant than electron impact. The partial charge exchange cross sections for carbon are however, very sensitive to beam energy.

Isler reported an anomalously high 4p population in Li-like O on the ISX-A tokamak at Oak Ridge (Isler and Crume 1978), and explained it through charge exchange recombination of O VII with background neutrals of low (10-400 ev) energy, an explanation that appears consistent with the data of de Heer which show the cross sections for populating 4p dominating at low energy.

Our model predicts large fractions of O VII in the plasma, which, but for this measurement would otherwise go undetected because O VII is a closed shell system which radiates only weakly until the electron temperatures become much larger.

A model of the charge state equilibrium of oxygen can supply us with realistic values of n_{he}/n_{li}. O VII is created by ionization from O VI and lost by charge exchange recombination with neutrals in the beam regions in which it spends 5-15% of its time, and by transport out of the plasma with time constant τ. The population of O VII is then, found from the equation,

$$\dot{n}_{he} = \emptyset = n_e n_{\ell i} \langle \sigma_{ion\ell i} v_e \rangle - \frac{n_{he}}{\tau} - \xi n_{he} n_b \sigma_{cx} v_b \quad , \tag{6}$$

where ξ is the fraction of its time which the ion spends in the neutral beam. We estimate ξ = 10% (±50%).

The TMX electron temperatures are low enough so that we can neglect ionization of O VII into O VIII as a loss mechanism. Solving for n_{he}/n_{li} gives,

$$\frac{n_{he}}{n_{\ell i}} = \frac{n_e \langle \sigma_{ion\ell i} v_e \rangle}{\xi n_b \sigma_{cx} v_b + \frac{1}{\tau}} \quad . \tag{7}$$

Using the recommended ionization rate coefficients of (Bell et al 1983) at T_e = 100 eV, $\langle \sigma_{ionO\ VI}\ v_e \rangle = 2.3 \times 10^{-10}$ cm^3/s. Taking $\sigma_{cx} = 30$ A^2,

$n_b = 5 \times 10^9\ cm^{-3}$, and $n_e = 5 \times 10^{12}\ cm^{-3}$, we find

$$\frac{n_{he}}{n_{\ell i}} = \frac{1.15}{\xi(1.5) + \frac{1}{\tau(\mathrm{msec})}} \quad . \tag{8}$$

This is plotted as a function of transport loss time τ in Fig. 5, for a likely range of beam intersection fractions ξ. For $\tau < 5$ msec, the O VII population is too low to explain the anomalous line ratio. Our measurements would require a confinement time of $\tau > 5$ ms to explain the ratios.

The same model may be applied to the steady state of O VI. Using measured values of n_{li}/n_{be}, where n_{be} is the beryllium-like fraction, can then give a value for the O VI confinement time. We must include ionization from O V and charge exchange recombination from O VII as source terms, and ionization to O VII along with charge exchange recombination to O V and transport in time τ as loss terms.

$$\begin{aligned} \mathring{n}_{\ell i} = \emptyset = n_e n_{be} \langle \sigma_{ion\,be} v_e \rangle + \xi n_{he} n_b \sigma_{cx} v_b \\ - \frac{n_{\ell i}}{\tau} - n_e n_{\ell i} \langle \sigma_{ion\,\ell i} v_e \rangle - \xi n_{\ell i} n_b \sigma_{cx} v_b \end{aligned} \tag{9}$$

where again ξ is the fraction of time the ion spends in the beam region. This gives

$$\frac{n_{\ell i}}{n_{be}} = \frac{n_e \langle \sigma_{ion\,be} v_e \rangle}{n_e \langle \sigma_{ion\,\ell i} v_e \rangle + \xi v_b n_b \sigma_{cx} \left(1 - \frac{n_{he}}{n_{\ell i}}\right) + \frac{1}{\tau}} \quad . \tag{10}$$

Inserting $\langle \sigma_{ion\,O\,V}\, v_e \rangle = 6 \times 10^{-10}\ cm^3/s$ at 100 eV, and using the same total charge exchange recombination cross-section (Crandall et al 1979) as for O VII gives

$$\frac{n_{\ell i}}{n_{be}} = \frac{3.\emptyset}{1.15 + 1.5\ \xi\ \left(1 - \frac{n_{he}}{n_{\ell i}}\right) + \frac{1}{\tau(\mathrm{msec})}} \quad . \tag{11}$$

In Fig. 7 we plot n_{he}/n_{1i} and n_{1i}/n_{be} versus confinement time, τ, for an ξ of 10%. On 1-20-83, an independent measurement (Yu) by a different EUV spectrometer, viewing O V and O VI spectra simultaneously, yields a value of n_{1i}/n_{be} = 7.0 (±30%). This value of n_{1i}/n_{be} = 7 implies a very long confinement time of τ = 25 msec, and n_{he}/n_{1i} = 6. 25 msec is much longer than the drag and loss cone scattering times of about 5 msec that should determine the confinement time on unplugged shots, and is probably not to be believed. However a value of n_{1i}/n_{be} of 5, within the error of the measurement, gives a more realistic τ of 10 msec. This is much more than the 1 msec confinement times observed on TMX (Strand 1982). The longer τ observed on TMX-U is due to central cell neutral beam heating, known to inject energetic magnetically confined oxygen, which was not present on the central cell of TMX. This ionization state balance model also predicts large enough values of O VII to explain the anomalous line ratio. A value of n_{he}/n_{1i} of 5 implies, for the shots considered, an oxygen impurity concentration of 3%.

CONCLUSION

Continued improvements in theoretical and experimental values for partial charge exchange cross sections will better enable spectroscopists to diagnose magnetically confined plasmas. By viewing spectra of Li-like impurities known to be excited by charge exchange with beam neutrals one can deduce concentrations of He-like impurities.

A better test of the model employed in this paper would be made by observing the 4 → 2 transitions in O VI which should be an order of magnitude more sensitive to charge exchange recombination excitation as compared to electron impact excitation than the 3 to 2 lines. If charge exchange recombination dominates over electron impact the 4 to 2 lines should be even stronger than the 3 to 2 lines. We did not perform this measurement as the plasma was not hot nor dense enough to produce O VII for the rest of 1983, and in 1984 we were constrained to move our line of sight out of the neutral beams.

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TABLE 1 Measured Values of τ for Different Elements

ION	$\tau = \frac{I(3d)}{I(3s)}$ (±50%)	T_e(eV)(±50%)	Date, Shot
O VI	3.5	100	1-20-83, 15
O VI	2.0	50	2-08-84, 28
C IV	1.6	-	2-15-83, 3
N V	2.3	100	8-25-84, 31

FIGURE CAPTIONS

Figure 1 Experimental arrangement.

Figure 2 Energy level diagram of Li-like sequence. Wavelength Values for O VI are listed in Angstroms. Branching ratios from n = 4 levels are indicated.

Figure 3 Anomalous O VI $\left(\frac{173Å}{184Å}\right)$ intensity line ratio on a hotter shot.

Figure 4 O VI $\left(\frac{173Å}{184Å}\right)$ intensity line ratio on a colder shot.

Figure 5 Oxygen $\frac{\text{O VII}}{\text{O VI}}$ relative population versus confinement time for various beam intersection times, ξ.

Figure 6 Oxygen $\frac{\text{O VII}}{\text{O VI}}$ and $\frac{\text{O VI}}{\text{O V}}$ relative population versus confinement time for ξ = 10%.

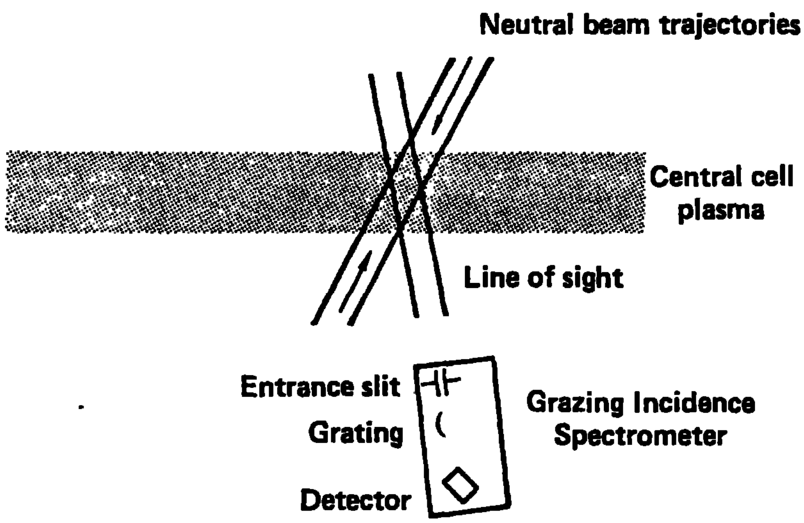

Neutral beam trajectories
Central cell
plasma
Line of sight
Entrance slit
Grating
Detector
Grazing Incidence
Spectrometer

Figure 1.

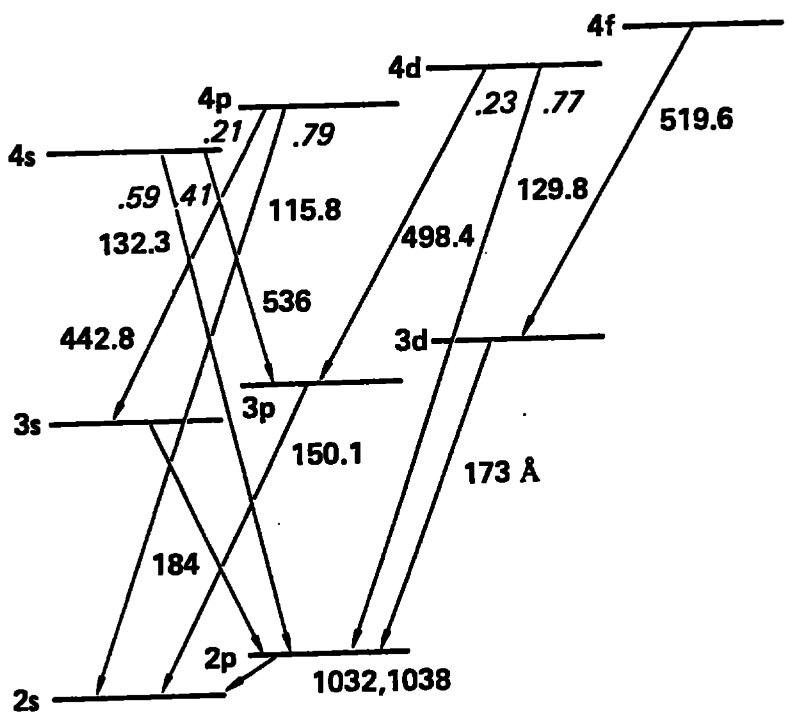
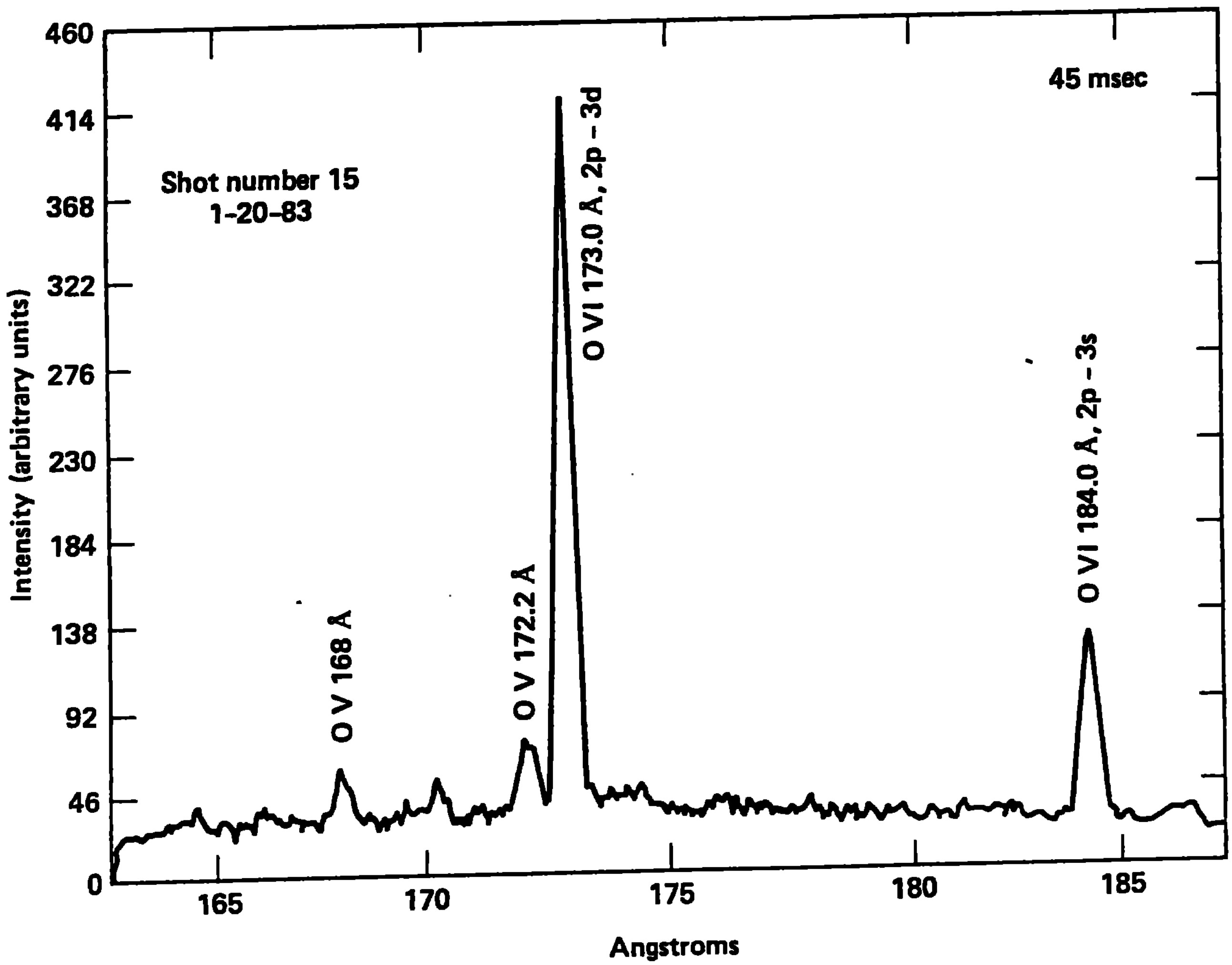
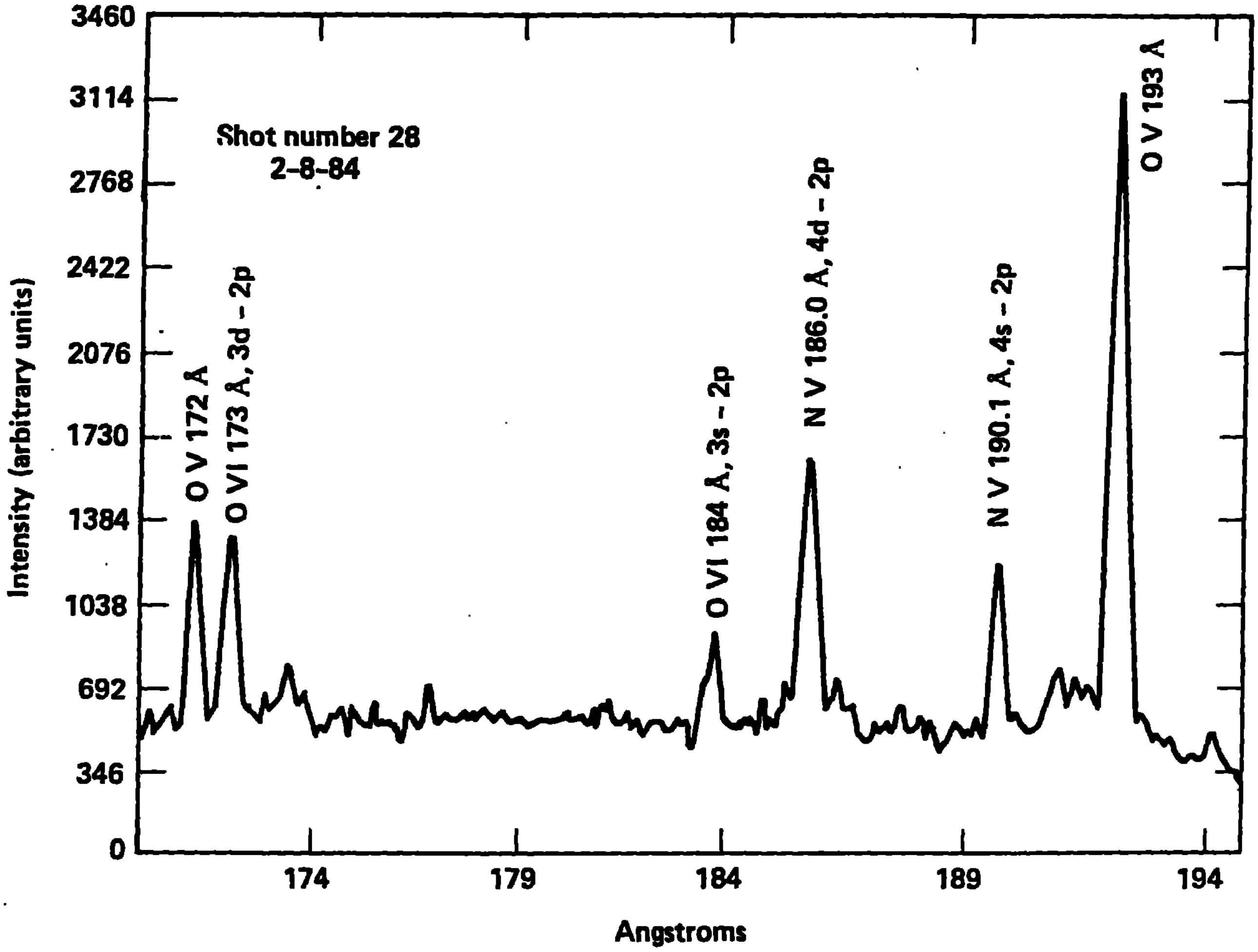

4f
4d
4p
4s
.21
.79
.23
.77
519.6
.59
.41
115.8
129.8
132.3
498.4
536
442.8
3d
3s
3p
150.1
173 Å
184
2p
2s
1032,1038

Figure 2



460
414
368
322
276
230
184
138
92
46
0
Intensity (arbitrary units)
Shot number 15
1-20-83
45 msec
O V 168 Å
O V 172.2 Å
O VI 173.0 Å, 2p – 3d
O VI 184.0 Å, 2p – 3s
165
170
175
180
185
Angstroms

Figure 3.



Shot number 28
2-8-84
Intensity (arbitrary units)
Angstroms
3460
3114
2768
2422
2076
1730
1384
1038
692
346
0
174
179
184
189
194
O V 172 Å
O VI 173 Å, 3d – 2p
O VI 184 Å, 3s – 2p
N V 186.0 Å, 4d – 2p
N V 190.1 Å, 4s – 2p
O V 193 Å

Figure 4.

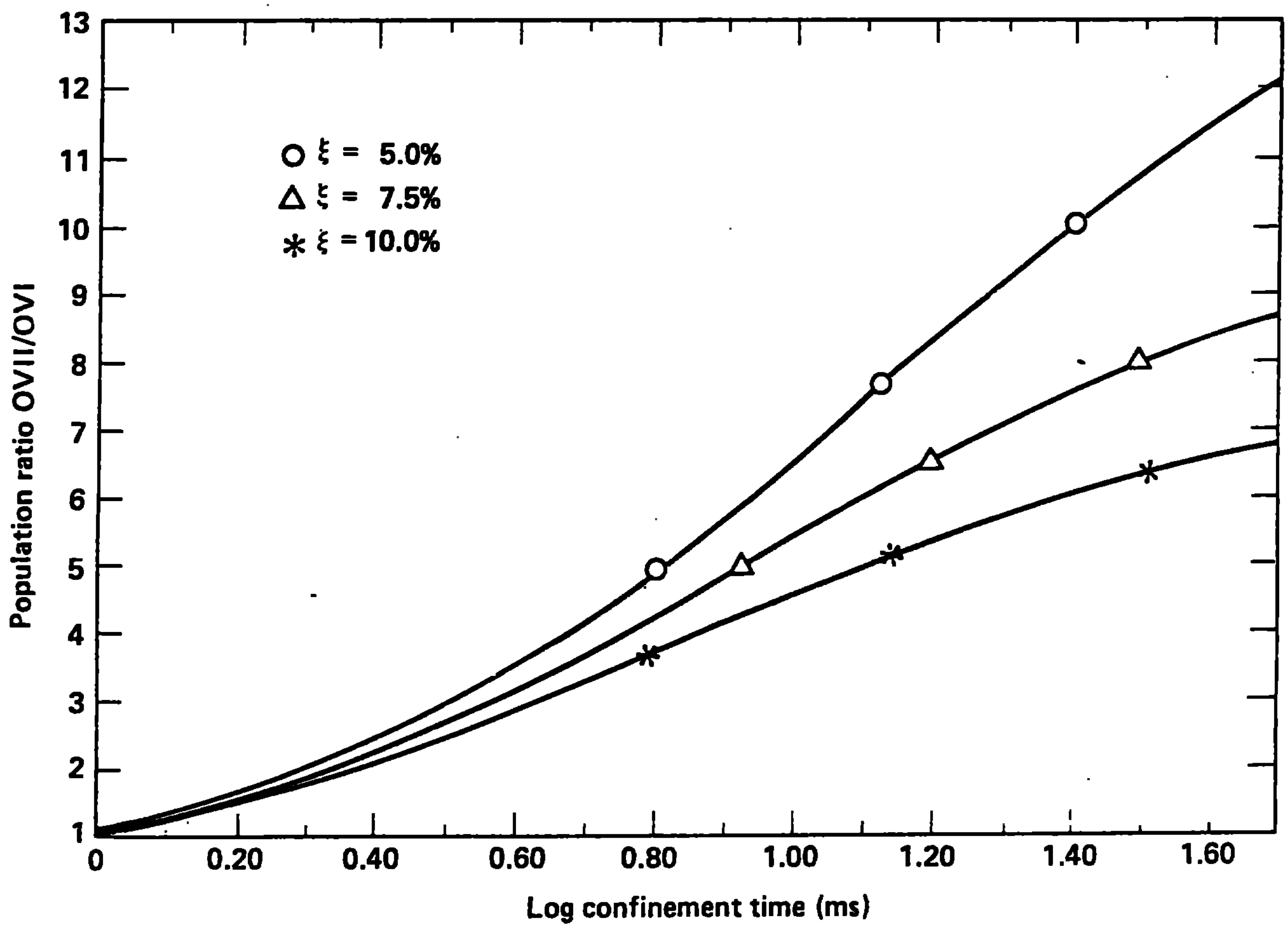
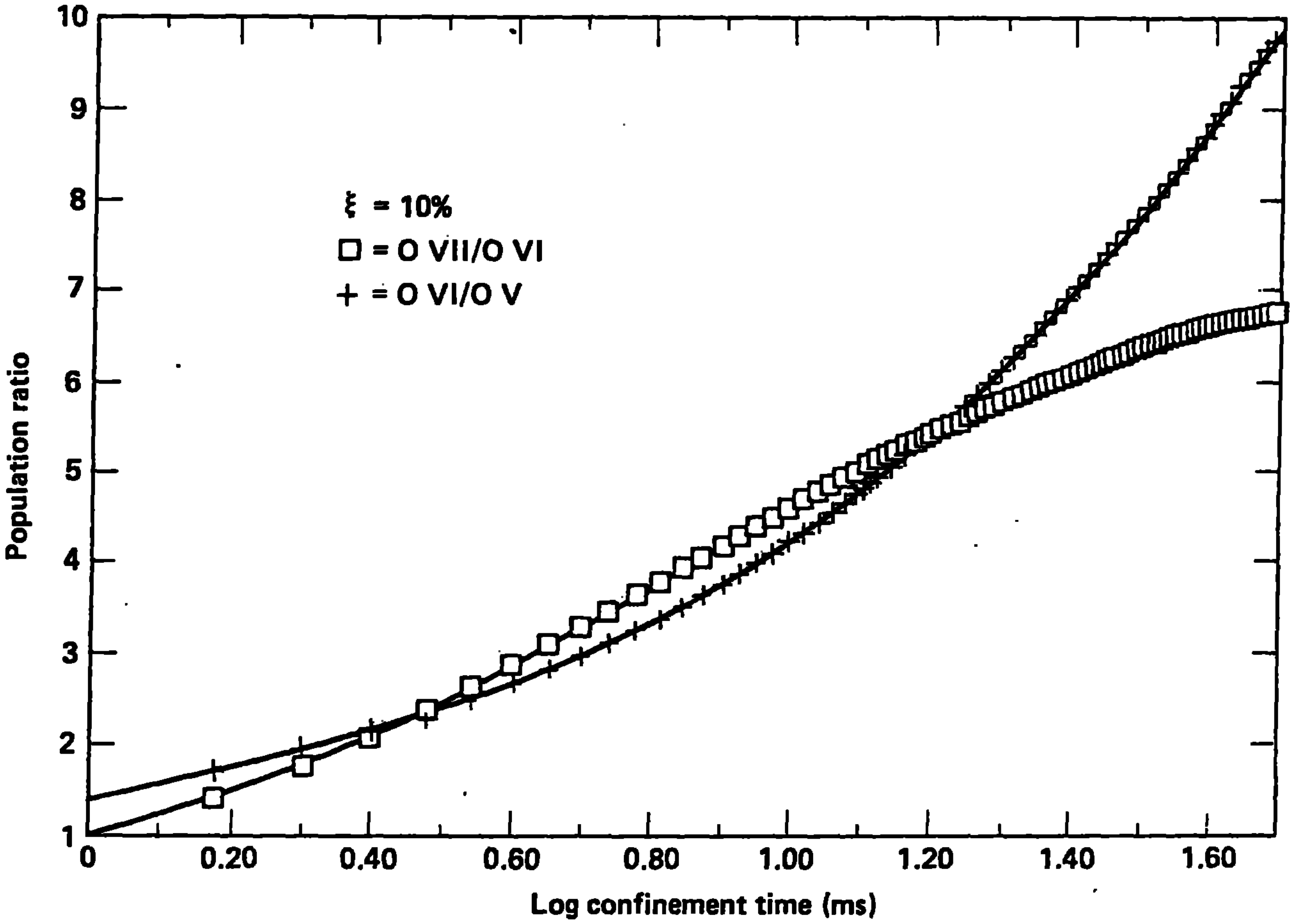

13
12
11
10
9
8
7
6
5
4
3
2
1
0
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
ξ = 5.0%
ξ = 7.5%
ξ = 10.0%
Population ratio OVII/OVI
Log confinement time (ms)

Figure 5.



10
9
8
7
6
5
4
3
2
1
0
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
Population ratio
Log confinement time (ms)
ξ = 10%
□ = O VII/O VI
+ = O VI/O V

Figure 6.